APPENDIX C:
DESIGN BASIS ELEMENTS AND GENERAL IMPLEMENTATION CONSIDERATIONS

1: SOIL--IN-SITU BIOREMEDIATION

Design Basis Elements

- Contaminant concentrations to determine nutrient requirements and period of performance (high contaminant concentrations can inhibit biodegradation, very low contaminant concentrations may not support biological activity; range of favorable concentrations varies by contaminant and site)
- Contaminant type to determine applicability and interferences (Kows greater than 1,000 are strongly sorbed to soil organic carbon and are less bioavailable)
- Contaminant types to determine oxygen needs (nonhalogenated aromatics, polynuclear aromatics, and nonhalogenated polar and nonpolar organics, generally are biodegraded more rapidly under aerobic conditions, certain halogenated aliphatics, halogenated aromatics, and polychlorinated biphenyls, or PCBs are more readily degraded anaerobically)
- Metals and radionuclides (generally not applicable)
- Multiple contaminants (presence of other contaminants; easily degradable contaminants will degrade first while more recalcitrant are left undegraded)
- Depth and areal extent of contamination (injection of nutrients is limited by drill-rig depth capabilities)
- Nutrient requirements (Nutrients that must be available in sufficient quantities for bioremediation to occur include C, H, O N, P, S, K, Ca, Fe, Mg, and Mn)
- Redox conditions (bioremediation can take place under aerobic or anaerobic conditions; aerobic biodegradation requires oxygen as the terminal electron acceptor (TEA) while anaerobic biodegradation uses TEAs such as NO_3^-, SO_4^{2-}, CO_2, Fe^{3+}, Mn^{4+}, oxygenated organics, and halogenated compounds)
- Rate-limiting nutrients (nitrogen and/or phosphorus are most frequently the rate-limiting nutrients in soil and are added to promote biodegradation, deficiencies of other nutrients are rare but should not be ignored)
- Bioaugmentation (soils typically contain the necessary soil bacterial communities to degrade contaminants; microbial additions may be desirable if the native community lacks the necessary bacteria to degrade the target compounds)
- Treatability tests (normally used to support remedy screening, selection, or design and to quantify biodegradation rates)
- Chemical and biological properties (COD and BOD are required to determine whether environmental conditions are conducive to microbial activity)
- Nutrient ratios (optimum carbon:nitrogen:phosphorus ratio is approximately 120:10:1; ratio is required to determine the need for additional nutrients)
- Oxygen (for an aerobic system require a minimum air-filled pore space of about 10 percent and soil gas oxygen concentrations greater than 5 percent)
- Temperature (generally, temperature should be in the range of 10 to 70 degrees

C for bioremediation to proceed)

- Moisture content (moisture contents < 40 percent of field capacity limit biological activity; moisture contents > 80 percent of field capacity reduce oxygen availability in soil)
- Soil physical characteristics (clay content greater than 10 percent may limit contaminant bioavailability and reduce biodegradation kinetics)
- Soil chemical characteristics (pH outside range of 4.5 to 8.5 limits biological activity)
- Soil organic carbon (SOC) content (high SOC content may limit contaminant bioavailability and reduce biodegradation kinetics)
- Site accessibility (helps determine maximum size of equipment)
- Presence of cultural resources/artifacts

General Implementation Considerations

- Process monitoring requirements (continuous monitoring is necessary to ensure that the appropriate ratios of nutrients are maintained)
- Regulatory requirements (faults, flood plains, artifacts, wetlands, wildlife refuge, etc.)
- Security requirements

2: SOIL--IN-SITU STABILIZATION

Design Basis Elements

- Depth and areal extent of contamination to determine volume requirements and limitations (in-situ mixing is limited by equipment torque capabilities; in-situ injection is limited by drill-rig depth capabilities)
- Depth of freezing (freeze/thaw cycles may impact efficacy of stabilization; stabilization mixtures above the freeze line may require special formulations)
- Depth of water table (contaminants located below the water table may require soil dewatering prior to stabilization)
- Soil temperatures (low temperatures (less than 5°C) may impede solidification process and result in substandard solidification products)
- Contaminant types (limited effectiveness for organic compounds, primarily suited to inorganic compounds e.g., metals, radionuclides)
- Contaminant concentrations (soils containing more than a few percent organic material may be difficult to stabilize and require special additives and/or increased quantities of stabilization agent)
- Contaminant volatility (additional safety precautions and or containment may be required due to contaminant volatilization caused by reagent heat of hydration)
- Radionuclide concentrations (cuttings brought to the surface may require measures to reduce and control worker risk)
- Soil physical characteristics (soil particle-size distribution, hydraulic conductivity, moisture content, plasticity, shear strength etc. are required to size equipment (auger size, power requirements, etc.) and select solidification reagents and estimate volumes and composition)
- Soil chemical characteristics (low pH soils may require neutralization prior to treatment with cement solidification reagents)
- Treatability study (normally used to determine appropriate solidification agents and mixing ratios, includes leaching data on treated and untreated soils to determine extent to which contaminant mobility is reduced)
- Site accessibility (helps determine maximum size of equipment)
- Space availability (technology has relatively large space requirements for equipment operations and material stockpiling)
- Surface structures (buildings etc., may prevent equipment access to site, angled or horizontal drilling with mixing has not been demonstrated)
- Post remediation options (may limit disposal and treatment options)
- Natural and waste debris (boulders, trees, buried drums and tanks can impede auger advancement)
- Contaminant/Reagent compatibility (sulfates, borates, or organic materials may interfere with the effectiveness of cementitious and pozzolanic reagents)

- Means of introducing reagent
- Reaction time
- Product stability (structural properties , chemical leachability, estimated life)
- Presence of cultural resources/artifacts

General Implementation Considerations

- Process monitoring requirements (continuous monitoring is necessary to ensure that the appropriate ratios of stabilizing agent to contaminated soil are maintained)
- Volume increases (volume increases due to addition of stabilization agent may impact final site grading)
- Regulatory requirements
- Security requirements
- Final closure (may require cap to limit infiltration and contaminant migration)
- Maintenance and monitoring (may require groundwater monitoring and post closure care of cap etc.)

3: SOIL--IN-SITU VITRIFICATION

Design Basis Elements

- Depth and areal extent of contamination to determine staging and limitations (maximum demonstrated melt depth is approximately 20 feet, dictates electrode placement and enhancement techniques)
- Volume reduction/backfill availability (typically 20 to 40% reduction in volume, will be necessary to backfill if it is desired to restore site to grade).
- Electrical requirements (3-phase, 12,500-13,800 V, 200 amps, special multiple-tap transformer that converts power to 2-phase and transforms it to required voltage)
- Type of contamination (organics containing sulfur, phosphorus, or halogens may generate acid gases requiring off-gas treatment, immiscible-phase organics may limit technology)
- Radionuclides (high Plutonium loading in soil may pose a criticality threat)
- Soil particle-size gradation and composition (must have 30% minimum SiO_2 and 1.4% minimum combined Na_2O and K_2O, additives may be required for certain soil types)
- Depth to groundwater (soil may need to be dewatered for high water tables and permeable soils prior to implementation)
- Location of underground structures(required to avoid electrical short circuits or damage to structures, heat protection may be required if structure is within 6 meters of melt zone)
- Treatability study (normally used to confirm that final product meets leachability requirements)
- Topography (equipment requires relatively flat topography (+/- 5% slope) within equipment staging area)
- Space availability (must have space for 3 full-size tractor trailers, power generation equipment (if required), and 17-meter wide off-gas collection hood)
- Metal concentration (should not exceed 5% of the melt weight material)
- Organic liquid content (should not exceed 1-7% depending on BTU value)
- Sealed containers (drums and tanks should be removed from area prior to treatment)
- Combustible solids (must be mixed with soil prior to treatment)
- Tritium (completely removed and released out stack)
- Radon, cesium, and other volatile and semi-volatile radionuclides (may present an exposure concern because of accumulation of off-gas system)
- Off-gas treatment requirements
- Electrode spacing
- Product stability (structural properties , chemical leachability, estimated life)

- Presence of cultural resources/artifacts

General Implementation Considerations

- Treated glass must meet TCLP requirement of RCRA
- Permitting/other legal requirements (if governing regulatory agency considers this incineration, a trial burn may be necessary)
- Security requirements

4: SOIL--SOIL VAPOR EXTRACTION

Design Basis Elements

- Depth of contaminated soil zone to determine extraction depth and limitations (when installing vent wells to depths < 10 feet a surface seal may be required to prevent drawing air from atmosphere instead of contaminated vadose zone)
- Areal extent of plume and access to install wells/piping system (buildings or utilities which may limit access)
- Presence/impact of underground utilities (do they act as preferential pathways, will they interfere with drilling/trenching/piping)
- Contaminant volatility (applicable to contaminants having vapor pressures greater than 0.5 mm Hg at ambient temperatures and dimensionless Henry's Law constants greater than 0.01)
- Soil permeability to determine radius of influence and flow rates (only applicable to permeable soils; soils with permeabilities to air flow exceeding 10^{-8} cm^2 [10^{-3} m/sec hydraulic conductivity] are commonly regarded as permeable)
- Soil moisture content (not applicable if liquid volume is equal to or greater than 90 percent of pore volume because air cannot be effectively transported through wet soils)
- Site uniformity (layers or abrupt changes is permeability limit effectiveness because air will move through more permeable areas and leave less permeable areas untreated)
- Site access for equipment (drilling, treatment plant)
- Depth to water table (only effective above water table; water table may have to be lowered if contamination extends below water table)
- Efficiency (up to 98 percent removal can be obtained, total removal not practical using this method)
- Soil organic carbon (high soil organic carbon contents limit its effectiveness)
- Removal times (ten days to three year time frames have been reported for maximum removal)
- Contaminant concentrations (required to determine removal rates and off-gas treatment needs)
- What type of surface seal is in place or can be used to prevent vertical short circuiting
- Soil character (site stratigraphy and porosity are required to determine radial influence and contaminant removal rates of wells)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, air permits)
- Volume of contaminated soil to be treated (number of wells, network of piping system)

- Air flow rate, layout of vent wells and pattern of soil air flushing through contaminated soil zone
- Pore volume flushing time for contaminated soil zone (volume of contaminated media divided by air extraction rate)
- Other properties affecting chemical removal (presence of NAPL, low permeability zones)
- Provision of suitable electric power for equipment (site electric service, capacity, transformers)
- Unit process steps for treatment (entrained liquid /condensate separation, heating for humidity control, contaminant removal, discharge)
- Treatability study (required during remedy screening and selection process to determine effectiveness)
- Combination of unit treatment processes (air extraction, conveyance, treatment, discharge, process control system)
- Residuals/waste streams generated (condensate water, chemicals removed in off-gas treatment system, discharge of treated air)
- Monitoring required (influent air stream, discharge air stream, flow rates and mass fluxes from wells)
- Handling of residuals(containerizing, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)

General Implementation Considerations
- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (condensate generation, freeze protection for any liquids generated)
- Operating procedures manual
- System optimization for maximum contaminant removal as conditions change
- Permitting/other legal requirements(applicable patents)
- Security requirements

5: SOIL--DIG AND TREAT WITH SOIL WASHING/SIZE SEPARATION

Design Basis Elements

- Depth of contamination (physical constraints of equipment, shoring requirements)
- Water table (Excavation of soils below the water table requires dewatering operations)
- Areal extent and access to excavate with equipment (buildings or above ground utilities which may limit access)
- Presence/impact of underground utilities (can utilities be shutdown and/or rerouted)
- Depth of contamination (treatable contamination depends on equipment and excavation technique; Draglines and backhoes can reach depths of 30-50 feet, clamshells can be used to 100 feet)
- Presence of cultural resources/artifacts
- Capacity (typically, 6-40 tons/hr of soil)
- Treatability studies (small-scale studies using site-specific soils and contaminants are the best way to predict effectiveness)
- Natural and waste debris (boulders, trees, and buried drums can impede site excavation)
- Contaminant properties (water solubility and chemical form are needed to help predict the contamination distribution in the Coarse and fine soil fractions)
- Types of contaminants (applicable to any contaminant retained in the fine-grained portion of the soil)
- Permits required (utility clearance, NPDES/Stormwater, excavation, air permits)
- Soil characteristics (clay soils may preclude use of soil separation because of limited volume reductions)
- Soil physical and chemical properties (particle size distribution, organic carbon content, and mineral composition needed to predict effectiveness, slope stability, etc.)
- Volume of soil to be treated (staging/storage areas required, throughput capacity of treatment process)
- Site access for equipment (excavation zone , staging area, treatment equipment, storage piles, backfill)
- Chemical characteristics of contaminants (low/high level radionuclides, mixed waste, metals, organics)
- Provision of suitable electric power for equipment (site electric service, capacity, transformers, portable generators)
- Unit process steps for treatment (initial screening, size separation, washing/separation vessels, filtering of wash liquor)

- Combination of unit treatment processes (materials handling/storage/movement through treatment steps)
- Residuals/waste streams generated (concentrated waste soil, wash liquor, filter material)
- Monitoring required (cleaned soil, concentrated waste soil, dust emissions, wash liquor)
- Handling of residuals(drumming, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)
- Restore site (backfill, recompaction, utility reconnect, resurfacing)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (freeze protection for process solutions, wind erosion protection for storage piles, runoff collection from storage piles)
- Fugitive dust emissions
- Operating procedures manual
- Permitting/other legal requirements
- Security requirements

6: SOIL--DIG AND TREAT STABILIZATION/SOLIDIFICATION

Design Basis Elements

- Depth of contamination (treatable contamination depends on equipment and excavation technique; Draglines and backhoes can reach depths of 30-50 feet, clamshells can be used to 100 feet)
- Removal rates (ranges from 5 - 400 yd^3/hr)
- Areal extent of contamination (larger excavations may require backhoes and draglines, clamshells are used for contamination that is narrow or of limited areal extent)
- Soil temperatures (low temperatures (less than 5°C) may impede solidification process and result in substandard solidification products)
- Water table (Excavation of soils below the water table requires dewatering operations)
- Contaminant types (limited effectiveness for organic compounds, primarily suited to inorganic compounds e.g., metals, radionuclides)
- Contaminant concentrations (soils containing more than a few percent organic material may be difficult to stabilize and require special additives and/or increased quantities of stabilization agent)
- Contaminant volatility (additional safety precautions and or containment may be required due to contaminant volatilization caused by reagent heat of hydration)
- Radionuclide concentrations (excavated materials brought to the surface may require measures to reduce and control worker risk)
- Strength and/or other waste acceptance criteria (strength typically required to evaluate physical stability and handling characteristics. EPA recommends unconfined compressive strength, UCS, of 50 psi.)
- Leachability (TCLP is required to determine whether a waste is hazardous because of its leaching characteristics)
- Solidification reagent/waste ratio (cement to waste ratios typically vary from 1:5 to 1:1; lime/ waste ratios from 5:100 to 30:100 ; bitumen/thermoplastic resin to waste ratios vary from 1:2 to 1:1)
- Volume increases (typical volume increases of 20 to 50 percent result from mixing reagent with waste)
- Permeability (permeabilities of stabilized material higher than 10^{-5} cm/s are usually unacceptable)
- Soil characteristics (soil type and strength are required to evaluate the side and bottom stability and design slope protection)
- Soil physical characteristics (soil particle-size distribution is required to select solidification reagents and estimate volumes and composition)
- Soil chemical characteristics (low pH soils may require neutralization prior to

treatment with cement solidification reagents)
- Bench-scale laboratory treatability study (usually performed to determine reagent/waste mix design)
- Obstructions (locations of utilities, structures, and other obstructions are required so that they can be avoided during excavation)
- Drums, debris, and tanks (special precautions are required when these items are present in the soil)
- Site accessibility (required to establish maximum size of equipment that can be used)
- Distance to treatment/disposal facility (needed to determine costs; increases in weight and volume from solidification process may render solidification uneconomical)
- Space availability (technology has relatively large space requirements for equipment operations and material stockpiling)
- Natural and waste debris (boulders, trees, buried drums and can impede site excavation)
- Contaminant/Reagent compatibility (sulfates, borates, or organic materials may interfere with the effectiveness of cementitious and pozzolanic reagents)
- Reaction time (curing time is required to estimate throughput)
- Product stability (structural properties , chemical leachability, estimated life)

General Implementation Considerations
- Process monitoring requirements (continuous monitoring is necessary to ensure that the appropriate ratios of stabilizing agent to contaminated soil are maintained)
- Slope protection may be required depending on excavation depth and soil type
- Fugitive dust emissions (must be controlled if site is near a populated area)
- Regulatory requirements
- Post remediation options (may limit disposal and treatment options)
- Security requirements
- Final closure (may require cap to limit infiltration and contaminant migration)
- Maintenance and monitoring (may require groundwater monitoring and post closure care of cap etc.)

7: SOIL--DIG AND TREAT - SOIL WASHING/CHEMICAL EXTRACTION

Design Basis Elements

- Depth of contamination (treatable contamination depends on equipment and excavation technique; Draglines and backhoes can reach depths of 30-50 feet, clamshells can be used to 100 feet)
- Volume of washing solution (usually 1-2 times volume of soil per washing step, several washing steps may be required depending on the removal efficiency of the washing solution and the desired residual levels in soils)
- Capacity (typically, 6 to 40 tons of soil per hour)
- Removal rates (ranges from 5 - 400 yd^3/hr)
- Types of contaminants (applicable to any contaminant that will partition into the wash solution, effectiveness is soil and contaminant specific)
- Areal extent of contamination (larger excavations may require backhoes and draglines, clamshells are used for contamination that is narrow or of limited areal extent)
- Water table (excavation of soils below the water table requires dewatering operations)
- Radionuclide concentrations (excavated materials brought to the surface may require measures to reduce and control worker risk)
- Bench-scale laboratory treatability study (small-scale studies usually conducted using site-specific soils and contaminants to determine effectiveness
- Contaminant properties (water solubility and chemical form are required to select washing reagents)
- Soil physical and chemical properties (needed to predict effectiveness and select equipment type and washing reagents)
- Soil volume (needed to size equipment)
- Obstructions (locations of utilities, structures, and other obstructions are required so that they can be avoided during excavation)
- Drums, debris, and tanks (special precautions are required when these items are present in the soil)
- Soil texture (clays may be hard to disperse which will increase reaction vessel size and washing time)
- Soil organic carbon content (high concentrations of organic carbon may decrease effectiveness because of adsorption of contaminants)
- Space availability (must be adequate for soil washing equipment and temporary storage of contaminated and washed soils)
- Natural and waste debris (boulders, trees, buried drums and can impede site excavation)
- Soil characteristics (clay soils may preclude the use of soil washing; soil minerals

may act as buffers and preclude the use of washing solutions that rely on acids or bases)

General Implementation Considerations

- Process monitoring requirements (continuous monitoring is necessary to ensure that appropriate ratios of washing solution to contaminated soil are maintained and that desired removal efficiencies are obtained)
- Slope protection may be required depending on excavation depth and soil type
- Wash solution may require treatment before disposal
- Fugitive dust emissions (must be controlled if site is near a populated area)
- Regulatory requirements
- Security requirements

8: SOIL--DIG AND HAUL FOR DISPOSAL

Design Basis Elements

- Depth of contamination (physical constraints of equipment, shoring requirements, proximity to water table; draglines and backhoes (modified) can reach depths of 30-50 feet, clamshells can reach depths of 100 feet)
- Removal rates (ranges from 5-400 yd^3/hr)
- Areal extent and access to excavate with equipment (buildings or above ground utilities which may limit access)
- Obstructions (locations of underground utilities, structures must be noted so they can be avoided during excavation and utilities can be shutdown and/or rerouted)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, NPDES/Stormwater, excavation, air permits)
- Volume of soil to be excavated (staging/storage areas required)
- Drums, debris, and tanks (special precautions are required when these items are present in the soil)
- Site access for equipment (excavation zone , staging area, storage piles, backfill)
- Physical characteristics of media (slope stability of excavation sidewalls)
- Chemical characteristics of media (low/high level radionuclides, mixed waste, metals, organics)
- Residuals/waste streams generated (waste soil, runoff from storage piles)
- Natural and waste debris (boulders, trees, and buried drums can impede site excavation)
- Monitoring required (waste soil, dust emissions)
- Distance to treatment/disposal facility (needed to determine costs)
- Disposal requirements (manifesting, transport & disposal of waste)
- Restore site (backfill, recompaction, utility reconnect, resurfacing)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (wind erosion protection for storage piles, runoff collection from storage piles)
- Suitable access routes for trucks to disposal facility
- Permitting/other legal requirements
- Security requirements

9: SOIL--CAPPING

Design Basis Elements

- Areal extent of contaminated zone and access to cap (buildings or utilities which may limit access)
- Presence of cultural resources/artifacts
- Soil cover (usually range in thickness from 2-4 feet of compacted clay with permeabilities less than 10^{-7} cm/sec; should be placed below frost line)
- Flexible membranes (usually range in thickness from 20-100 mils; typically placed below frost layer)
- Slopes (top slope is usually from 3-5 percent after allowing for settling or subsidence)
- Contaminant characterization (required to assure that cap addresses all contaminant hazards e.g., thickness to mitigate radiation hazards)
- Erosion control (vegetative covers are used if climate will support them; if not, armored covers are used)
- Biointrusion layers (required when intrusion from burrowing animals is a problem; consists of large pebbles)
- Effectiveness (reduce infiltration for clay caps to 3 cm or less per year while more elaborate designs may reduce infiltration to 0.5 cm/year or less)
- Combined topsoil/native soil layer (combined thickness is the greater of 2 feet or the depth of frost penetration)
- Granular drainage layer (thicknesses range from 0.5 to 5 feet; may not be required if soil protective layer is adequate)
- Temperature fluctuations (large temperature fluctuations may cause cracking in synthetics because of a large coefficient of thermal expansion)
- Volatile gas generation (some wastes may generate gases that require venting through cap)
- Potential waste volume changes (changes in waste volume through settling or gas generation may affect waste performance; stabilization may be required to preclude problems with waste volumes)
- Local climate (wind speeds, precipitation data are needed to design cap and covers)
- Permits required (utility clearance, excavation, air permits)
- Surface structures (types and locations of surface structures are required to account for these structures in cap design)
- Adjacent sites (locations of adjacent sites are required to assure that runoff is properly managed and whether a single cap is desirable or if multiple caps are preferable)
- Runoff collection system from capped area

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Permitting/other legal requirements
- Security requirements, access restrictions after capped is placed
- Cap maintenance (long-term cap maintenance will be required; includes surface and perimeter monitoring)

10: SOIL--BIOVENTING

Design Basis Elements

- Depth of contaminated soil zone (vent well construction depths, screen intervals, shallow contamination or groundwater may preclude this technology because of diminished radius of influence and cheaper alternatives)
- Areal extent of plume and access to install wells/piping system (buildings or utilities which may limit access)
- Presence/impact of underground utilities (do they act as preferential pathways, will they interfere with drilling/trenching/piping)
- Types of contaminants (contaminants susceptible to aerobic biodegradation; not applicable to inorganic elements and compounds)
- Concentrations of contaminants (contaminant concentrations too high may inhibit biological activity while concentrations too low may not support biological activity)
- Contaminant source (should be eliminated to the extent possible before beginning bioventing)
- Presence of multiple contaminants (an easily degradable contaminant will be degraded first leaving behind more recalcitrant undegraded contaminants)
- Solubility (contaminants with aqueous solubility less than 1 mg/l are difficult to biodegrade)
- High hydrophobicity (contaminants with Kows greater than 1,000 are difficult to biodegrade because they are highly adsorbed to organic carbon and less available)
- Site access for equipment (drilling, treatment plant)
- Time to complete remediation (most economically-feasible systems achieve remediation in 1-3 years; may not be appropriate if a short (< 6 months) cleanup time is required)
- Soil permeability (with soils not very permeable to air flow (i.e., permeability < 10^{-11} cm^2) oxygen delivery and biodegradation rates will be low)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, air permits)
- Volume of contaminated soil to be treated (number of wells, network of piping system)
- Layout of vent wells and pattern of soil air flushing and oxygen delivery through contaminated soil zone
- Rate of oxygen delivery to contaminated soil zone
- Properties affecting biodegradation rate (moisture content, pH, other nutrients)
- Other properties affecting chemical degradation (presence of NAPL, low permeability zones)
- Physical characteristics of media (hydraulic conductivity of soil, radial influence of vent wells, pressure induced in vent wells)

- Chemical characteristics of media (low/high level radio nuclides, mixed waste, metals, organics)
- Provision of suitable electric power for equipment (site electric service, capacity, transformers)
- Unit process steps for treatment (air injection, monitoring)
- Monitoring required (air injection rates, 0_2 and $C0_2$ levels in soil gas)
- Handling of residuals(containerizing, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (condensate generation, freeze protection for any liquids generated)
- Operating procedures manual
- System optimization for maximum contaminant removal as conditions change
- Permitting/other legal requirements(applicable patents)
- Security requirements

11: GROUND WATER--PUMP AND TREAT

Design Basis Elements

- Depth of ground water plume (well construction depths, screen intervals, lift requirements for submersible pumps and type of system employed; suction-lift pumps are only effective to 15-20 feet)
- Areal extent and depth of contamination (required to determine number of wells, placement and design)
- Types of contaminants (determine removal rates, treatment type and discharge limitations)
- Presence/impact of underground utilities (do they act as preferential pathways, will they interfere with drilling/trenching/piping)
- Soil characteristics (porosity, organic carbon content, hydraulic conductivity, and grain-size distribution are required to determine how contaminant will partition between the aqueous and gaseous phases)
- Aquifer characterization (storativity, permeability, gradient, flow direction, and available drawdown required for good well design)
- Presence of other well fields or surface water bodies (to determine if drawdown in pumping wells will impact flow patterns of other wells and/or water levels)
- Site access for equipment (well drilling, treatment plant)
- Casing diameters (chosen to accommodate pump and prevent uphole water velocities greater than 1.5 m/sec; typical diameters range from 4-inch that can handle up to 200 gal/minute at 1.5 m/sec to 24-inch that can supply up to 6,500 gal/minute at 1.5 m/sec)
- Screens and open area (may range from 5 percent open area for high-strength screens with small openings to 75 percent for low-strength screens with large openings)
- Multiple aquifers (groundwater extraction from a single aquifer may have adverse effects because gradients created can cause contamination of other aquifers)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, air permits, NPDES, water resource use)
- Pore volume flushing time of contaminated ground water zone (plume volume divided by pumping rate)
- Hydraulic conductivity (soils with hydraulic conductivities less than 10^{-4} cm/sec are difficult to remediate because of a limited ability to extract water)
- Other properties affecting chemical removal (presence of NAPL, low permeability zones)
- Seasonal or intermittent pumping schedules of water use wells in the area
- Chemical characteristics of media (low/high level radio nuclides, mixed waste,

metals, organics, presence of other water quality parameters [iron, calcite, etc.] which indicate potential for scale formation in piping/treatment equipment)

- Provision of suitable electric power for equipment (site electric service, capacity, transformers)
- Unit process steps for treatment (pretreatment, contaminant removal, polishing treatment)
- Combination of unit treatment processes (extraction, conveyance, treatment, discharge, process control system)
- Off-gas treatment requirements (air stream dehumidifying, carbon adsorption efficiency, oxidation system)
- Residuals/waste streams generated (chemicals removed, discharge of treated water)
- Monitoring required (influent water, treated water, contaminant waste stream)
- Handling of residuals (containerizing, labeling, storage)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (freeze protection for process solutions)
- Operating procedures manual
- Permitting/other legal requirements
- Security requirements

12: GROUND WATER--IN-WELL STRIPPING WITH RECIRCULATING WELLS

Design Basis Elements

- Depth of ground water plume (generally should be 10 feet or greater to provide sufficient space to recharge water; well construction depths, extraction and recharge screen intervals, submersion requirements for pumping)
- Areal extent and depth of plume and access to install wells/piping system (buildings or utilities which may limit access)
- Presence/impact of underground utilities (do they act as preferential pathways, will they interfere with drilling/trenching/piping)
- Stratigraphy (impervious layers between the vadose-zone discharge point and the water table will require specialized designs)
- Hydraulic conductivity (must be greater than 10^{-4} cm/sec to move sufficient water)
- Contaminant strippability (contaminant should have a Henry's Law constant greater than 5×10^{-4} atm-m^3/mole)
- Site access for equipment (well drilling, treatment plant)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, air permits)
- Plume volume of contaminated ground water to be treated (number of wells, network of piping system)
- Pore volume flushing time of contaminated ground water zone (plume volume divided by pumping rate)
- Properties controlling chemical desorption from soil (retardation of chemical movement/recovery in flushing calculations)
- Other properties affecting chemical removal (presence of NAPL, low permeability zones)
- Physical characteristics of media (possible presence of low permeability lenses in plume, hydraulic conductivity/yield of aquifer, treatment zone of recirculating wells, drawdown in pumping wells, grain-size distribution for screen and filterpack sizing)
- Chemical characteristics of media (low/high level radio nuclides, mixed waste, metals, organics, presence of other water quality parameters [iron, calcite, etc.] which indicate potential for scale formation in recharge zones)
- Provision of suitable electric power for equipment (site electric service, capacity, transformers)
- Off-gas treatment requirements (air stream dehumidifying, carbon adsorption efficiency, oxidation system)
- Residuals/waste streams generated (chemicals removed, condensate water collected)
- Monitoring required (influent water, treated water, off-gas air stream before and after

treatment)
- Handling of residuals(containerizing, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)

General Implementation Considerations
- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (freeze protection for process streams)
- Operating procedures manual
- Permitting/other legal requirements (applicable patents for technology)
- Security requirements

13: GROUND WATER--DUAL-PHASE EXTRACTION

Design Basis Elements

- Depth of ground water plume (well construction depths, extraction intervals, vacuum and lift requirements for pumping)
- Areal extent of plume and access to install wells/piping system (buildings or utilities which may limit access)
- Presence/impact of underground utilities (do they act as preferential pathways, will they interfere with drilling/trenching/piping)
- Aquifer permeability (generally should be 10^{-4} cm/sec or lower so that water renters treatment zone slowly)
- Site access for equipment (well drilling, treatment plant)
- Types of contaminants (generally applicable to contaminants with Henry's Law constants greater than 2.5 X 10^{-4} atm.-m^3/mole or vapor pressures greater than 1 mm Hg. at ambient temperatures)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, air permits, NPDES, water resource use)
- Plume volume of contaminated ground water to be treated (number of wells, network of piping system)
- Pore volume flushing time of contaminated ground water zone (plume volume divided by pumping rate)
- Properties controlling chemical desorption from soil (retardation of chemical movement/recovery in flushing calculations)
- Other properties affecting chemical removal (presence of NAPL, low permeability zones)
- Physical characteristics of media (hydraulic conductivity/yield of aquifer, capture zone from extraction well, drawdown in pumping wells, grain-size distribution for screen and filterpack sizing)
- Chemical characteristics of media (low/high level radio nuclides, mixed waste, metals, organics, presence of other water quality parameters [iron, calcite, etc.] which indicate potential for scale formation in equipment)
- Provision of suitable electric power for equipment (site electric service, capacity, transformers)
- Unit process steps for treatment (liquid/gas phase separation, pretreatment, contaminant removal, polishing treatment)
- Combination of unit treatment processes (extraction, conveyance, treatment, discharge, process control system)
- Off-gas treatment requirements (air stream dehumidifying, carbon adsorption efficiency, oxidation system)

- Residuals/waste streams generated (chemicals removed, condensate water collected)
- Monitoring required (influent water, treated water, off-gas air stream before and after treatment)
- Handling of residuals(containerizing, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)
- Weather related considerations (freeze protection for process streams)
- Operating procedures manual
- Permitting/other legal requirements (applicable patents for technology)
- Security requirements

14: GROUND WATER--CONTAINMENT BARRIERS

Design Basis Elements

- Depth to bottom of ground water plume (total depth of barrier wall, presence of an aquitard to tie in base of barrier wall)
- Areal extent of plume and access to install barrier system (buildings or utilities which may limit access)
- Surface capping to prevent precipitation infiltration into contained area
- Presence/impact of underground utilities (will they interfere with barrier construction/installation, can they be shutdown/rerouted)
- Types of contaminants (applicable to all contaminants present in groundwater)
- Wall permeability (typical values for wall permeability range from 10^{-6} to 10^{-7} cm/sec)
- Wall thickness (24 - 48 inches is typical for slurry, soil mixed, and jetted wall)
- Slurry levels during construction (height of slurry wall should be maintained 2 to 4 feet above groundwater level to maintain trench stability)
- Backfill slope range (typical horizontal to vertical backfill slope ranges from 6:1 to 10:1)
- Site access for construction equipment (excavator, slurry mix area, driving hammer for sheet pile)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, NPDES/stormwater)
- Linear length and depth of barrier to be installed (total square feet of barrier required)
- Physical characteristics of the soil (grain-size distribution for slurry mix, blow counts and density for sheet pile)
- Chemical characteristics of contaminated ground water (compatibility with slurry wall, corrosion potential for sheet pile wall)
- Residuals/waste streams generated during construction (excavated soils)
- Protection from burrowing animals
- Slope and surface with respect to surface water runon and runoff
- Vegetative cover
- Water budget from contained/capped area
- Monitoring required (hydraulic head inside and outside of contained area, contaminant concentrations outside of contained area)
- Handling of residuals(containerizing, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)
- Restore site(backfill, recompaction, utility reconnect, resurfacing)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)

- Weather related considerations (wind erosion protection for storage piles, runoff collection from storage piles, difficulties in system construction in heavy precipitation)
- Permitting/other legal requirements
- Security requirements

15: GROUND WATER--IN-SITU PERMEABLE TREATMENT ZONE BARRIERS

Design Basis Elements

- Depth to bottom of ground water plume (total depth of barrier wall, presence of an aquitard to tie in base of barrier wall)
- Areal extent of plume and access to install barrier system (buildings or utilities which may limit access)
- Presence/impact of underground utilities (will they interfere with barrier construction/installation, can they be shutdown/rerouted)
- Site access for construction equipment (excavator, driving hammer for sheet pile)
- Presence of cultural resources/artifacts
- Permits required (utility clearance, excavation, NPDES/stormwater)
- Linear length, depth and thickness of barrier to be installed (total square feet and volume of barrier required)
- Physical characteristics of the aquifer and permeable media (travel time to and across permeable reaction zone)
- Chemical characteristics of contaminated ground water (plugging/fouling/precipitates)
- Installation as a funnel and gate approach or as a complete permeable barrier treatment wall (conceptual configuration and hence permeable cross section and flux rates)
- Groundwater flux through the barrier 9 required media permeability)
- Residence time in the barrier treatment zone (thickness and capacity of media)
- Chemistry of treatment/removal in the permeable segment (identify interferences and residency requirements)
- Life of the treatment media (determine need to replenish or regenerate media)
- Anticipated period of performance (determine capacity or regeneration requirements)
- Means of regenerating/replacing treatment media if relevant (logistics of regenerating media)
- Residuals/waste streams generated during construction(excavated soils)
- Monitoring required (contaminant concentrations upgradient and downgradient of permeable wall)
- Handling of residuals(containerizing, labeling, storage)
- Disposal requirements (manifesting, transport & disposal of waste)
- Restore site(backfill, recompaction, utility reconnect, resurfacing)

General Implementation Considerations

- H&S, PPE requirements for dealing with exposure potential (airborne dust, dermal contact, vapors)

- Weather related considerations (wind erosion protection for storage piles, runoff collection from storage piles)
- Permitting/other legal requirements (applicable patents for technology)
- Security requirements

16: GROUNDWATER--IN-SITU BIOREMEDIATION

Design Basis Elements

- Location (contaminant location in relation to ground surface and water table determines bioreclamation approach)
- Weather (infiltration rates may affect dissolved oxygen levels)
- Site hydrology (ability to deliver nutrients and terminal electron acceptors to contaminated subsurface zone is affected by permeability; minimum permeability should be > 10^{-3} cm/sec)
- Contaminant concentrations (high contaminant concentrations can inhibit biodegradation, very low contaminant concentrations may not support biological activity; range of favorable concentrations varies by contaminant and site)
- Particle-size distribution (extreme heterogeneity in soil particle-size distribution leads to inconsistent bioreclamation of contaminated media)
- Contaminant types (most frequently used to treat soil/water systems contaminated with gasoline, diesel, jet fuel, and BTEX. Cometabolic biodegradation of chlorinated aliphatic solvents has also been demonstrated)
- Contaminant types (certain halogenated aliphatics, halogenated aromatics, and polychlorinated biphenyls, or PCBs are more readily degraded anaerobically)
- Metals and radionuclides (generally not applicable)
- Multiple contaminants (presence of other contaminants; easily degradable contaminants will degrade first while more recalcitrant contaminants are left undegraded)
- Depth and areal extent of contamination (injection of nutrients is limited by drill-rig depth capabilities)
- Rate-limiting nutrients (nitrogen and/or phosphorus are most frequently the rate-limiting nutrients in soil and are added to promote biodegradation, deficiencies of other nutrients are rare but should not be ignored)
- Bioaugmentation (soils typically contain the necessary soil bacterial communities to degrade contaminants; microbial additions may be desirable if the native community lacks the necessary bacteria to degrade the target compounds)
- Substrate addition (adding substrates such as methane and phenol has been demonstrated effective for the aerobic oxidation of chlorinated solvents through cometabolism)
- Treatability tests (normally used to support remedy screening, selection, or design and to quantify biodegradation rates)
- Redox potential (redox potential greater than 50 mV for aerobic/facultative system; < 50mV for anaerobic system)
- Terminal electron acceptor (aerobic biodegradation requires oxygen as the terminal

electron acceptor (TEA) while anaerobic biodegradation uses TEAs such as NO_3^-, SO_4^{2-}, CO_2, Fe^{3+}, Mn^{4+}, oxygenated organics, and halogenated compounds)

- Chemical and biological properties (COD and BOD are required to determine whether environmental conditions are conducive to microbial activity)
- Nutrient ratios (optimum carbon:nitrogen:phosphorus ratio is approximately 120:10:1; ratio is required to determine the need for additional nutrients)
- Oxygen (for an aerobic system, dissolved oxygen concentrations should be > than 1 mg/l; < 1 mg/l for an anaerobic system)
- Oxygen (may need to add hydrogen peroxide to injection system to increase oxygen concentrations; care is needed as hydrogen peroxide is toxic to bacteria at high concentrations. Hydrogen peroxide at 40 mg/l has been reported to provide sufficient oxygen without inhibiting bacterial growth)
- Temperature (generally, temperature should be in the range of 10 to 70 degrees C for bioremediation to proceed) biodegradation kinetics)
- Soil chemical characteristics (pH outside range of 4.5 to 8.5 limits biological activity)
- Soil organic carbon (SOC) content (required to determine sorption characteristics of aquifer soil which may impact contaminant bioavailability and mobility)

General Implementation Considerations

- Reinjected water augmented with nutrients, etc. (must be reinjected into the aquifer from which it was extracted and meet standards similar to surface water discharge standards if practicable.
- Process monitoring requirements (continuous monitoring is necessary to ensure that the appropriate ratios of nutrients are maintained)
- Regulatory requirements (faults, flood plains, artifacts, wetlands, wildlife refuge, etc.)
- Security requirements